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(54) Cascaded raman resonator system and apparatus

Verfahren und Vorrichtung mit kaskadiertem Ramanresonator

Appareil et système avec résonateur Raman en cascade

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Description

Background of the Invention

1. Field of the Invention

[0001] The invention relates to optical amplifiers and lasers. More particularly, the invention relates to optical amplifier and laser apparatus and methods using cascaded Raman resonators.

2. Description of the Related Art

[0002] Optical amplifiers and lasers are used within optical communications systems to compensate for losses incurred throughout the system. Optical amplifiers often include a Raman amplifier or laser to pump light at a particular wavelength. See, for example, U.S. Patent No. 5,323,404.

[0003] In general, Raman amplifiers and Raman lasers are based on stimulated Raman scattering, a non-linear optical process that involves converting light from an optical source to the vibrational modes of a non-linear optical transmission medium (for example, an optical fiber, typically a silica-based optical fiber) and re-radiation at a different (typically longer) wavelength.

[0004] For example, a cascaded Raman laser typically is a Raman laser with a non-linear optical transmission medium that has, in addition to a pair of reflectors that defines an optical cavity for radiation of an output wavelength λ_n, at least one Raman-Stokes order reflector pair defining a corresponding optical cavity for radiation of wavelength $\lambda_{n-1} < \lambda_n$, where $n \geq 2$. The reflector pairs are, for example, Bragg gratings, etched gratings or in-line refractive index gratings. When fused silica is used as the non-linear medium, the maximum Raman gain occurs at a frequency shift of 13.2 terahertz (THz), which corresponds to a wavelength shift of approximately 50-100 nanometers (nm) for pump wavelengths between approximately 1.0 and 1.5 microns (μm).

[0005] A cascaded Raman resonator (CRR) includes a non-linear optical transmission medium to generate Raman laser energy at a specific output wavelength (λ_n). More specifically, the cascaded Raman resonator converts light from an optical source such as a pump laser operating at a pump wavelength (λ_p) to the desired output wavelength (λ_n).

[0006] Suitable applications of such cascaded Raman resonator include, for example, remotely pumped erbium (Er) fiber amplifiers in repeaterless optical fiber communication systems.

[0007] However, conventional cascaded Raman resonators typically require optical sources that operate at a specific pump wavelength (λ_p) depending on the cascaded Raman resonator output wavelength (λ_n) desired. For example, a cascaded Raman resonator having an output wavelength (λ_n) of 1480 nm typically is useful only with an optical source such as a pump laser operating at a pump wavelength (λ_p) of 1117 nm, which corresponds to a series of resonators spaced at wavelengths corresponding to the maximum Raman gains or frequency shifts of about 13.5 THz. Similarly, a cascaded Raman resonator having an output wavelength (λ_n) of 1450 nm typically is useful only with an optical source such as a pump laser operating at a pump wavelength (λ_p) of 1100 nm.

[0008] Thus, it would be desirable to have available Raman laser devices that are power scaleable and more independent of the device input wavelength (λ_p). Such devices would be more versatile in that, for example, the devices would not be limited to use with sources having only a specific pump wavelength (λ_p) that corresponds to a Raman-Stokes order that leads to the desired output wavelength (λ_n) of the device.

Summary of the Invention

[0009] The invention is as defined by the claims. Embodiments of the invention include an apparatus for converting light within an optical fiber communications system. Embodiments of the invention provide a cascaded Raman resonator (CRR) or other suitable Raman frequency shifting device having an optical energy transmission medium with a series of Raman-Stokes order reflectors and an output reflector therein. One or more of the reflectors are written to provide conversion with less than maximum efficiency, but sufficient efficiency to allow different pump laser wavelengths to be converted thereby. For example, the reflectors within the cascaded Raman resonator are written at wavelengths that are not necessarily at the maximum of the Raman gain for the pump wavelength (λ_p) but still provide sufficient conversion efficiency

[0010] In one embodiment of the invention, a cascaded Raman resonator includes an optical fiber with an optical cavities defined by a pump reflector and a pair of highly reflective gratings whose maximum reflectance wavelength does not correspond to the wavelength where the theoretical maximum Raman gain occurs but is within an acceptable range for sufficient conversion efficiency. Alternatively, one or more of the reflectors in the series of intermediate Raman-Stokes reflectors and the low reflectivity output reflector are not necessarily written at wavelengths that correspond to the theoretical maximum Raman gain but are within acceptable ranges thereof for sufficient conversion efficiency.

[0011] According to another alternative embodiment of the invention, the cascaded Raman resonator does not use a pump reflector. More specifically, when operating at sufficiently high pump powers, for example, greater than approximately 4 watts, sufficient conversion exists over approximately the first 500 meters of fiber that the pump reflector, typically written within at the pump wavelength (λ_p), is not necessary.

[0012] Cascaded Raman resonators designed in accordance with embodiments of the invention are useful

with different pump lasers having different pump wavelengths (λ_p). For example, 1480 nm cascaded Raman resonators, which conventionally convert optical energy from 1117 nm pump lasers to an output signal wavelength of 1480 nm, also are useful for converting optical energy from, for example, 1100 nm pump lasers to the output signal wavelength of 1480 nm.

[0013] Alternatively, when operated at low pump powers, for example, less than approximately 4 watts, 1480 nm cascaded Raman resonators (CRR) include an additional high reflectance grating written at approximately 1100 nm to reflect the non-absorbed light. In this manner, 1480 nm cascaded Raman resonators are useful with, for example, 1100 nm pump laser sources in addition to 1117 nm pump lasers. In conventional arrangements, 1100 nm pump lasers typically are used only with 1450 nm cascaded Raman resonators, which conventionally are designed to convert optical energy from 1100 nm pump lasers to an output signal wavelength of 1450 nm.

[0014] Also, in a similar manner, according to embodiments of the invention, 1450 nm cascaded Raman resonators, which conventionally convert optical energy from 1100 nm pump lasers to an output signal wavelength of 1450 nm, also are useful in converting optical energy from 1117 nm pump lasers to the output signal wavelength of 1450 nm. Alternatively, when operated at low pump powers, for example, less than approximately 4 watts, 1450 nm cascaded Raman resonators include an additional high reflectance grating written at approximately 1117 nm to reflect the non-absorbed light. In conventional arrangements, 1117 nm pump lasers typically are used only with 1480 nm cascaded Raman resonators, which conventionally are designed to convert optical energy from 1117 nm pump lasers to an output signal wavelength of 1480 nm.

[0015] Cascaded Raman resonator (CRR) devices according to embodiments of the invention are power scaleable in a manner sufficient to provide adequate optical power for a variety of application at a desired output wavelength for a given plurality of pump wavelengths. Also, the devices according to embodiments of the invention are less complex and less expensive than conventional arrangements.

Brief Description of the Drawings

[0016] In the drawings:

FIG. 1 is a simplified schematic diagram of a typical optical fiber laser system;

FIGS. 2a-b are simplified schematic diagrams of conventional optical fiber laser system arrangements;

FIG. 3 is a graphical diagram of the Raman gain spectrum for an optical transmission medium of fused silica fiber and a pump wavelength of approximately 1 μm;

FIG. 4 is a simplified schematic diagram of an optical fiber laser system according to an embodiment of the invention;

FIG. 5 is a simplified schematic diagram of an optical fiber laser system according to another embodiment of the invention;

FIG. 6a is a graphical diagram of light absorption versus optical fiber length for high pump powers;

FIG. 6b is a graphical diagram of light absorption versus optical fiber length for low pump powers; and

FIG. 7 is a simplified schematic diagram of an optical fiber laser system according to an alternative embodiment of the invention.

Detailed Description

[0017] In the following description similar components are referred to by the same reference numeral in order to enhance the understanding of the invention through the description of the drawings.

[0018] Although specific features, configurations and arrangements are discussed hereinbelow, it should be understood that such is done for illustrative purposes only. A person skilled in the relevant art will recognize that other steps, configurations and arrangements are useful without departing from the scope of the invention as defined by the claims.

[0019] Embodiments of the invention are based on the advantageous realization that light converted with less than theoretically maximum efficiency still is sufficient for many optical fiber laser applications. Accordingly, at least one of the reflective grating pairs written on the optical energy transmission medium contained within a Raman frequency shifting device is not necessarily written in direct correspondence with the theoretical maximum gain of the intermediate Stokes orders. Such realization is used to fabricate, for example, cascaded Raman resonators (CRR) and other suitable optical conversion devices that are power scaleable in a manner sufficient to provide optical fiber amplification (via Raman shifts) at a desired output wavelength for a given plurality of pump lasers operating at different pump wavelengths.

[0020] Also, embodiments of the invention are based on the advantageous realization that, with respect to pumped light versus optical fiber length at sufficient pump powers, for high pump powers, for example, greater than approximately 4 watts, the pumped light is significantly if not effectively completely absorbed in the first hundred meters of the optical fiber. Therefore, when operating at such high pump powers, a pump reflector often is not needed within the optical conversion device.

[0021] Referring now to FIG. 1, an optical fiber laser system 10 is shown. The optical fiber laser system 10 includes, for example, a cascaded Raman resonator (CRR) 12 that is adapted for receiving optical energy from a pump laser 14 at a pump wavelength of λ_p and converting the optical energy to output optical energy at

an output wavelength of λ_n. The pump laser includes, for example, a high power diode laser 16 and a cladding pumped fiber laser 18. The components of the pump laser 14 are given for illustration purposes only and are not meant to be a limitation of embodiments of the invention. It should be understood that, in accordance with embodiments of the invention, the pump laser 14 can have conventional structure. A suitable pump laser is, for example, a 1117 nanometer (nm) cladding pumped fiber laser (CPFL).

[0022] The cascaded Raman resonator 12 includes a length of optical fiber 32 or other suitable optical transmission medium having at least one reflective grating set written to an output region 34 thereof and at least one reflective grating set written to an input region 36 thereof. The reflective gratings are, for example, Bragg gratings, etched gratings, in-line refractive index gratings or other suitable highly reflective fiber reflecting means. From another perspective, the cascaded Raman resonator 12 shown in Fig. 1 includes a set or plurality of matched fiber Bragg gratings spliced to both ends of the fiber 32.

[0023] The fiber grating set written to the output region 34 of the optical fiber 32 includes, for example, at least one highly reflective pump grating 42 whose maximum reflectance wavelength is approximately equal to the pump wavelength (λ_p) from the pump laser 14. Also, the output fiber grating set includes highly reflective gratings 44 whose maximum reflectance wavelengths essentially correspond to wavelengths within the intermediate Stokes orders (λ_{n-1}, λ_{n-2}, λ_{n-3},...) that correspond to maximum gain. The output fiber grating set also includes at least one low reflectance or transmissive grating 46 whose minimum reflectance is approximately equal to the desired output wavelength (λ_n) of the optical fiber laser system 10.

[0024] The fiber grating set written to the input region 36 of the optical fiber 32 includes highly reflective gratings 52 whose maximum reflectance wavelengths essentially correspond to wavelengths within the intermediate Stokes orders (λ_{n-1}, λ_{n-2}, λ_{n-3},...) that correspond to maximum gain. Also, the input fiber grating set includes at least one highly reflective grating 54 whose maximum reflectance wavelength is approximately equal to the desired output wavelength (λ_n).

[0025] As was discussed previously herein, the maximum gain of the intermediate Stokes orders occurs at frequency shifts of about 13.2 terahertz (THz), starting at, for example, the operating wavelength of the pump laser (λ_p). Shifts of 13.2 THz correspond to a wavelength shifts of approximately 50-100 nanometers (nm) for pump wavelengths between approximately 1.0 and 1.5 microns (μm). The power of the intermediate Raman-Stokes orders is circulated into the cavity ofthe cascaded Raman resonator 12 until it is almost entirely converted into the successive Raman-Stokes orders. For example, in operation, the optical fiber laser system 10 shown in FIG. 1 receives from the pump laser 14 at the pump wavelength λ_p and efficiently converts the optical energy to output optical energy at an output wavelength λ_n.

[0026] Referring now to FIG. 2a, a conventional optical fiber laser system arrangement 20 is shown. The arrangement 20 includes a pump laser 14 having an input, operating or pump wavelength (λ_p) of approximately 1117 nm. The pump laser 14 is connected, for example, by a splice (indicated generally by "x") to a cascaded Raman resonator (CRR) 12.

[0027] The cascaded Raman resonator 12 includes a length of optical fiber 32 having an output region 34 with at least one refractive index grating written thereto and an input region 36 with at least one refractive index grating written thereto. The output region 34 includes a plurality of highly reflective gratings 44 with center wavelengths of approximately 1175 nm, 1240 nm, 1310 nm and 1396 nm. The output region 34 also includes a pump reflector, for example, in the form of a high reflectance grating 42, having a maximum reflectance wavelength of approximately 1117 nm, which is, for example, approximately equal to the operating wavelength λ_p of the pump laser 14. The output fiber grating set also includes at least one low reflectance or transmissive grating 46 whose minimum reflectance is approximately equal to the desired output wavelength (λ_n) of the optical fiber laser system 20.

[0028] The input region 36 includes a plurality of highly reflective gratings 52 with center wavelengths of approximately 1175 nm, 1240 nm, 1310 nm and 1396 nm. The input region 36 also includes at least one highly reflective grating 54, whose maximum reflectance is 1480 nm, that is, approximately equal to the desired output wavelength λ_n.

[0029] The reflective gratings 52 of the input region 36 combine with the corresponding reflective gratings 44 of the output region 34 to define optical cavities therebetween that allow for the Raman scattering, as disclosed previously herein. More specifically, the reflective gratings 44, 52 are written so that their center wavelengths correspond to the intermediate Raman-Stokes orders between the pump wavelength (λ_p = 1117 nm) and the output wavelength (λ_n = 1480 nm). In operation, the conventional arrangement of FIG. 2a converts input optical energy having an input or pump wavelength of 1117 nm to output optical energy having a wavelength of 1480 nm.

[0030] Referring now to FIG. 2b, a conventional optical fiber arrangement 22 using a pump laser 14 having a wavelength (λ_p) of approximately 1100 nm is shown. The arrangement 22 also includes a cascaded Raman resonator 12 operably connected thereto, for example, by a splice (indicated generally by "x").

[0031] The cascaded Raman resonator 12 includes an optical fiber 32 having an output region 34 and an input region 36. The output region 34 includes a plurality of highly reflective gratings 44 with center wavelengths of approximately 1156 nm, 1218 nm, 1287 nm, and 1366

nm, and a pump reflector, for example, in the form of a high reflectance grating 42, having a maximum reflectance wavelength of approximately 1100 nm (the operating or pump wavelength λ_p of the pump laser 14). The output fiber grating set also includes at least one low reflectance or transmissive grating 46 whose minimum reflectance is approximately equal to the desired output wavelength (λ_n) of the optical fiber laser system 20.

[0032] The input region 36 includes a plurality of highly reflective gratings 52 with center wavelengths of approximately 1156 nm, 1218 nm, 1287 nm, and 1366 nm. The region 36 also includes at least one highly reflective grating 54, whose maximum reflectance is 1480 nm, that is, approximately equal to the desired output wavelength λ_n.

[0033] The reflective index gratings written to the input and output regions 36, 34 of the optical fiber 32 are written so that the respective maximum reflectance wavelengths (that is, their center wavelengths) correspond to the intermediate Raman-Stokes orders (that is, 1156 nm, 1218 nm, 1287 nm, 1366 nm) between the input pump wavelength (1100 nm) and the output wavelength (1450 nm). In operation, the optical fiber arrangement 22 shown in FIG. 2b converts input optical energy having an input or pump wavelength of 1100 nm to output optical energy having a wavelength of 1450 nm.

[0034] As should be evident from the previous discussion of the conventional arrangements shown in Figs. 2a-b, in conventional arrangements, the input and output regions 36, 34 are configured to be useful only with an input source having a specific operating wavelength. For example, the arrangement 20 shown in Fig. 2a is useful only with a pump laser 14 having an operating (pump) wavelength λ_p of approximately 1117 nm. Similarly, the arrangement 22 shown in Fig. 2b is useful only with a pump laser 14 having a operating (pump) wavelength λ_p of approximately 1100 nm. Thus, in order to obtain a different desired output wavelength λ_n, a different input wavelength (and thus a different pump laser) is required. Therefore, in conventional arrangements, cascaded Raman resonators typically are useful only with a single pump laser operating at a certain wavelength.

[0035] From an economic perspective, the cascaded Raman resonator represents approximately 40% of the total cost of the overall optical fiber laser system arrangement. Therefore, the pump laser contributes approximately 60% of the total cost, and each additional pump laser required in addition to the initial pump laser adds an additional 60% to the overall cost of the of the optical fiber laser system.

[0036] According to embodiments of the invention, light is converted using stimulated Raman scattering at wavelengths characterized by less than maximum but sufficient conversion efficiency for many optical fiber laser applications. In this manner, the usefulness of optical energy sources such as pump lasers is expanded advantageously. For example, pump lasers that conventionally were useful only with a single cascaded Raman resonator (CRR) configuration, are, according to embodiments of the invention, useful with multiple cascaded Raman resonator (CRR) configurations.

[0037] Referring now to FIG. 3, a graph 30 of the Raman gain spectrum is shown. From the graph 30, it is seen that Raman gain occurs for frequency shifts up to 42 THz with the "practical" Raman gain spectrum extending from approximately 3 THz until 15 THz, but with less efficient operation than is achievable at a frequency shift corresponding to the maximum Raman gain. Therefore, according to embodiments of the invention, cascaded Raman resonators and other suitable optical fiber laser devices are configured in such a way that the frequency shifts of the resonant cavities fall within this frequency range, but not necessarily at the frequency that provides the theoretically maximum conversion efficiency. More specifically, one or more gratings or other reflective means are written so that their center wavelengths do not necessarily correspond to the maximum gain of the Raman-Stokes orders. Such configurations expand the usefulness of cascaded Raman resonators and other suitable devices in certain applications to the extent that, for example, devices designed for a pump laser or other optical energy source operating at a specific wavelength are useful with sources that operate at other wavelengths.

[0038] For example, in accordance with embodiments of the invention, cascaded Raman resonators have pump reflectors, output reflectors and Raman-Stokes order reflectors that take into account non-maximized but sufficient frequency shifts within the illustrated frequency range. That is, one or more of the grating pairs that form these reflectors are not necessarily written in correspondence with maximum gain of the intermediate Stokes orders of one or more pump laser operating wavelengths. However, the gratings are written within acceptable ranges of the theoretical maximum reflectance wavelengths, therefore allowing less efficient but still sufficient light conversion from an input or pump wavelength λ_p to a desired output wavelength λ_n. In this manner, a single cascaded Raman resonator is flexible enough to convert light to a desired output wavelength λ_n from more than one pump laser wavelength (for example, λ_{p1}, λ_{p2}), unlike conventional cascaded Raman resonator arrangements.

[0039] Referring now to FIG. 4, an optical fiber laser system arrangement 40 according to an embodiment of the invention is shown. The arrangement 40 includes an optical energy source such as a pump laser 14 having an input or pump wavelength (λ_p) of, for example, 1100 nm, 1117 nm or other suitable wavelength, for example, within the range from approximately 1085 nm to 1130 nm. The pump laser 14 is connected to a cascaded Raman resonator (CRR) 12, for example, by a splice (indicated generally by "x").

[0040] The cascaded Raman resonator 12 includes an optical transmission medium such as an optical fiber

32 having an output region 34 and an input region 36. The output region 34 includes a pump reflector, for example, in the form of a high reflectance grating 42, written within the output region 34 with the maximum reflectance occurring at a wavelength of approximately 1117 nm. As will be discussed in greater detail hereinbelow, the high reflectance pump grating 42 makes it possible for the cascaded Raman resonator 12 to provide 1480 nm lasing for an input wavelength of 1117 nm (that is, a 1117/1480 CRR).

[0041] According to an alternative embodiment of the invention, the output region 34 also includes another pump reflector, for example, in the form of a high reflectance grating 43, written within the output region 34 with the maximum reflectance occurring at a wavelength of approximately 1100 nm. As will be discussed in greater detail hereinbelow, the high reflectance pump grating 42 and/or the high reflectance grating 43 allows the cascaded Raman resonator 12 to provide 1480 nm lasing for an input wavelength of 1100 nm (that is, a 1100/1480 CRR).

[0042] The output region 34 also includes a plurality of reflective gratings 44 written within the output region 34 design to reflect at wavelengths that at least roughly correspond to Raman-Stokes order wavelength shifts. For example, as shown, the reflective gratings 44 in the output region 34 have center wavelengths of approximately 1175 nm, 1240 nm, 1310 nm and 1396 nm. However, according to embodiments ofthe invention, one or more of the reflective gratings 44 are written, for example, so that their center wavelengths do not correspond to the maximum gain of the Raman-Stokes order wavelength shifts, but rather correspond to shifts within approximately ±20 nm of the theoretical Raman shifts for maximum gain, which provide less than theoretically ideal but still enough conversion efficiency for the given application.

[0043] The output region 34 also includes at least one low reflectance or transmissive grating 46 whose minimum reflectance is approximately equal to the desired output wavelength (λ_n) of the optical fiber laser system 40, for example, approximately 1480 nm, which corresponds to the Raman-Stokes order wavelength shift. However, according to embodiments of the invention, the low reflectance or transmissive grating 46 is written, for example, so that its maximum reflectance does not correspond to the gain maximum of the Raman-Stokes order wavelength shift (1480 nm), that is, 1480 nm ±20 nm.

[0044] It should be noted that, according to embodiments of the invention, although one or more of the gratings 52 in the input region 36 and gratings 44 in the output region 34 do not correspond gain maxima of the Raman-Stokes orders, they should still match or complement one another. That is, gratings 52, 44 should still define optical cavities as before. For example, if a grating 44 in the output region is written for maximum reflectance at, for example, 1245 nm (instead of the theoretical 1240 nm), then the corresponding grating 52 in the input region 36 should likewise be written for maximum reflectance at 1245 nm. In this manner, the defined optical cavity needed for proper Raman scattering is maintained.

[0045] The input region 36 includes a plurality of highly reflective gratings 52 written to match or complement the plurality of reflective gratings 44 in the output region 34, that is, to correspond at least roughly to the Raman-Stokes order wavelength shifts. More specifically, both the reflective gratings 44 and the reflective gratings 52 are written to have center wavelengths of approximately 1175 nm, 1240 nm, 1310 nm and 1396 nm.

[0046] The input region 36 also includes a high reflectance output reflector, for example, in the form of a high reflectance grating 54. The high reflectance grating 54 is written within the input region 36 so that the maximum reflection of the high reflectance grating occurs at approximately the desired output wavelength λ_n.

[0047] In operation, the reflective gratings 52 ofthe input region 36 combine with the corresponding reflective gratings 44 of the output region 34 to define optical cavities therebetween that allow for the Raman scattering, as disclosed previously herein. More specifically, the input optical energy from the pump laser 14 (for example, having an input wavelength λ_p of approximately 1100 nm or 1117 nm) propagates essentially unimpeded through the input region 36. The optical energy then is substantially converted to 1175 nm by Raman scattering in the region of the optical fiber 32 between the input region 36 and the output region 34. Any light that initially is not converted is reflected by the highly reflective grating 42 (1117 nm) and/or the highly reflective grating 43 (1100 nm) back into the optical cavity defined by the two 1175 nm gratings.

[0048] The (converted) 1175 nm light then is reflected back into the region of the optical fiber 32 between the input region 36 and the output region 34 by the two 1175 nm gratings, where it is substantially converted to 1240 nm by Raman scattering. The 1240 nm light then is reflected back into the region of the optical fiber 32 between the input region 36 and the output region 34 by the two 1175 nm gratings, where it is substantially converted to 1310 nm by Raman scattering. Similarly, the 1310 nm light is converted to 1396 nm and then to 1480 nm.

[0049] The (converted) 1480 nm light, which propagates at the desired output wavelength (λ_n) is reflected by the highly reflective grating 54 in the input region 36. The 1480 nm light then passes through the low reflectance or transmissive grating 46 and the rest of the output region 34 to the output of the resonator 12.

[0050] In conventional arrangements, the high reflectance pump reflector grating is written to have maximum reflectance wavelengths approximately equal to the pump laser wavelength (λ_p). The Raman-Stokes order reflector gratings are written based on the theoretical maximum frequency shifts for maximum gain from the

desired input wavelength (λ_p) and the low reflectance output reflector gratings are written to have satisfactory reflectance corresponding to the desired output wavelength (λ_n).

[0051] For example, in conventional arrangements, for a pump laser with an operating wavelength of 1100 nm, the pump reflector is written for maximum reflectance to occur at a wavelength of 1100 nm. Also, the Raman frequency shifts which correspond to maximum gain occur, for example, at wavelengths of 1156 nm, 1218 nm, 1287 nm and 1366 nm and thus the Raman-Stokes order reflector gratings are written to correspond with these frequency shifts. Finally, the output reflector grating is written for minimum reflectance to occur at a wavelength of 1450 nm. See, for example, FIG. 2a and the corresponding discussion hereinabove.

[0052] Similarly, in conventional arrangements, for a pump laser with an operating wavelength of 1117 nm, the pump reflector is written to have maximum reflectance at a wavelength of 1117 nm. Also, the Raman frequency shifts which correspond to maximum gain occur, for example, at wavelengths of 1175 nm, 1240 nm, 1310 nm and 1396 nm and thus the Raman-Stokes order reflector gratings are written to correspond with these frequency shifts. The output reflector grating is written for minimum reflectance to occur at a wavelength of 1480 nm. See, for example, FIG. 2b and the corresponding discussion hereinabove.

[0053] However, embodiments of the invention advantageously recognize that the Raman gain spectrum is approximately 60 nm wide. Therefore, for example, a pump laser operating at a wavelength of 1100 nm provides gain from, for example, 1120 nm to 1180 nm. Such gain is within an acceptable range for cascaded Raman resonators designed for operation with, for example, a 1117 nm pump laser (that is, a 1117/1480 CRR), wherein the maximum gain for the first Raman shift from 1117 nm occurs at 1175 nm. Therefore, according to embodiments of the invention, a 1117/1480 CRR configured, for example, as shown in Fig. 4, is capable of being pumped not only by a 1117 nm pump laser (as is conventionally done), but also by a 1100 nm pump laser as well.

[0054] Similarly, the 60 nm wide gain spectrum is sufficient for cascaded Raman resonators designed for operation with 1100 nm pump lasers (that is, 1100/1450 CRRs) to be pumped not only by 1117 nm pump lasers (as is conventionally done), but also by a 1100 nm pump laser. A 1100/1450 CRR configured according to embodiments of the invention is shown in Fig. 5 as part of the optical fiber laser system arrangement 50.

[0055] The optical fiber laser system arrangement 50 includes an optical energy source such as the pump laser 14 having a pump wavelength (λ_p) of approximately 1100 nm. The pump laser 14 is connected to a cascaded Raman resonator (CRR) 12. The cascaded Raman resonator 12 includes the optical fiber 32 with an output region 34 and an input region 36. The output region 34 includes a pump reflector (for example, high reflectance grating 42) written so that its maximum reflectance occurs at approximately 1100 nm.

[0056] According to embodiments of the invention, the output region 34 also includes another pump reflector, for example, in the form of a high reflectance grating 45, written in the output region 34 so that its maximum reflectance occurs at a wavelength of approximately 1117 nm. It is the addition of the high reflectance grating 45 that allows the cascaded Raman resonator 12 to provide 1450 nm lasing for an input wavelength of 1117 nm (that is, a 1117/1450 CRR).

[0057] The reflective gratings 44 written in the output region 34 correspond, at least roughly, to Raman-Stokes order wavelength shifts corresponding to maximum gain. Thus, for a 1100/1450 CRR, the reflective gratings 44 have center wavelengths of approximately 1175 nm, 1240 nm, 1310 nm and 1396 nm for theoretical maximum Raman scattering conversion efficiency. However, according to embodiments of the invention, one or more of the reflective gratings 44 do not correspond to maximum gain Raman-Stokes order wavelength shifts, but rather correspond to shifts that provide less than theoretically ideal but still conversion efficiency for the given application. More specifically, one or more of the gratings 44 are written within ±20 nm of the previously-mentioned center wavelengths.

[0058] The output region 34 also includes at least one low reflectance or transmissive grating 46 written to its maximum reflectance at approximately 1450 nm. However, according to an embodiment of the invention, the transmissive grating 46 is written, for example, so that its maximum reflectance does not correspond to the gain maximum of the Raman-Stokes order wavelength shift (1450 nm). For example, grating 46 is written to have its maximum reflectance at 1450 ±20 nm.

[0059] The input region 36 includes a plurality of highly reflective gratings 52 written, for example, to have center wavelengths of approximately 1175 nm, 1240 nm, 1310 nm and 1396 nm for theoretical maximum Raman scattering conversion efficiency. The input region 36 also includes a high reflectance grating 54 written so that the maximum reflection of the high reflectance grating occurs at approximately 1450 nm (that is, λ_n). However, according to an embodiment of the invention, at least one of the gratings 52 and/or grating 54 is written, for example, so that its maximum reflectance does not correspond to the gain maximum of the Raman-Stokes order wavelength shift (1450 nm). More specifically, one or more of the gratings 52, 54 are written within ±20 nm of the previously-mentioned center wavelengths.

[0060] As discussed previously herein, although one or more of the gratings 52 and 44 do not correspond to the gain maxima of the Raman-Stokes orders according to embodiments of the invention, the gratings should still match or complement their corresponding gratings. That is, gratings 52, 44 should still define optical cavities as before. For example, if a grating 44 in the output re-

gion 34 is written for maximum reflectance at, for example, 1360 nm (instead of the theoretical 1366 nm), then the corresponding grating 52 in the input region 36 should likewise be written for maximum reflectance at 1360 nm. In this manner, the defined optical cavity needed for proper Raman scattering is maintained.

[0061] In operation, the optical fiber laser system arrangement 50 converts input light having at an input wavelength (λ_p) of 1100 nm to light having an output wavelength (λ_n) of 1450 nm, in a conventional manner. However, according to embodiments of the invention, the optical fiber laser system arrangement 50 also converts light having an input wavelength (λ_p) of 1117 nm to light having an output wavelength (λ_n) of 1450.

[0062] The advantageous realization according to embodiments of the invention also allows the writing of one or more of the Raman-Stokes order reflector grating pairs to vary based on the conversion frequency needed within the cascaded Raman resonator rather than solely on theoretical maximum gain Raman frequency shifts. Similarly, it is possible to vary the writing of the high reflectance pump reflectors and/or the low reflectance output reflectors depending on the needed conversion frequency instead of only theoretical maximum gain Raman frequency shifts.

[0063] Referring now to FIGs. 6a-b, graphs of simulated pump absorption versus optical fiber length for various pump power intensities are shown. From the graph in Fig. 6a it can be seen that, for relatively high pump powers (for example, pump powers greater than approximately 4 watts), most of the light practically is absorbed within, for example, the first 100 meters of the optical fiber. Therefore, according to alternative embodiments of the invention, a pump reflector is not required when operating, for example, at relatively high pump powers (for example, greater than 4 watts). By comparison, as shown in Fig. 6b, it can be seen that, for lower pump powers, much of the light is not absorbed by the fiber, even after approximately 500 meters.

[0064] Referring now to FIG. 7, an optical fiber laser system arrangement 70 according to an alternative embodiment of the invention is shown. Specifically, the optical fiber laser system arrangement 70 combines the use of the cascaded Raman resonator 12 with a pump laser 14 that operates at relatively high pump powers (for example, greater than 4 watts). As shown, the optical fiber laser system arrangement 70 includes an optical fiber 32 having an output region 34 and an input region 36. The output region 34 includes a plurality of gratings 44 written, for example, to at least roughly correspond to the intermediate Stokes orders (λ_{n-1}, λ_{n-2}, λ_{n-3},...). Similarly, the input region 36 includes a plurality of gratings 52 written, for example, to at least roughly correspond to the intermediate Stokes orders (λ_{n-1}. λ_{n-2}, λ_{n-3},...). Also, the input region 36 includes a highly reflective grating 54 whose maximum reflectance wavelength is approximately equal to the desired output wavelength (λ_n).

[0065] However, according to this alternative embodiment of the invention, the cascaded Raman resonator 12 does not include a pump reflector. As discussed previously herein, for pump lasers 14 operating at high pump powers, (for example, greater than approximately 4 watts) sufficient absorption occurs in the first hundred meters of the optical fiber such that a pump reflector often is not needed within the light conversion device. Accordingly, if the pump power is relatively low (for example, less than approximately 4 watts), a pump reflector corresponding to the particular wavelength of the pump laser (λ_p) may have to be written at the output grating set.

[0066] The inventive cascaded Raman resonator arrangement 70 shown in FIG. 7 is compared with, for example, the inventive arrangement 40 shown in FIG. 4, in which the cascaded Raman resonator 12 includes the pump reflector 42 written to have maximum reflectance at a wavelength of 1117 nm, and the inventive arrangement 50 shown in FIG. 5, in which the cascaded Raman resonator 12 includes the pump reflector 42 written to have maximum reflectance at a wavelength of 1100 nm.

[0067] Optical fiber laser system arrangements and devices according to embodiments of the invention are less complex and less expensive than conventional arrangements. Furthermore, the scaleable power features of arrangements according to embodiments of the invention offer additional flexibility.

[0068] It will be apparent to those skilled in the art that many changes and substitutions can be made to the embodiments of the optical fiber laser system arrangements and devices herein described without departing from the scope of the invention as defined by the appended claims.

Claims

1. Apparatus for converting optical energy within an optical communications system (10) including a source of optical energy (14) having an input wavelength λ_p, wherein the optical energy is Raman converted to an output wavelength λ_n that is greater than the input wavelength λ_p, wherein said apparatus comprises:

   an optical transmission medium (32) coupled to the source of optical energy;
   at least one pair of gratings (44, 46, 52, 54) formed in said optical transmission medium that defines optical cavities for radiation of optical energy at said output wavelength λ_n, wherein the defined optical cavities convert optical energy of the input wavelength λ_p optical energy having the output wavelength λ_n,

   characterized in that
   at least one pair of the gratings is written in

said optical transmission medium at a wavelength that does not correspond to the maximum gain for the Raman-Stokes order shift wherein the optical energy is converted with less efficiency than if the gratings were written at wavelengths that correspond to the maximum gain for the Raman-Stokes order shifts wherein maximum reflection efficiency occurs at wavelengths that correspond to Raman-Stokes order shifts.

2. The apparatus as recited in claim 1, further comprising a reflective grating formed in said optical transmission medium at a wavelength that provides maximum reflection of optical energy at the input wavelength λ_p.

3. The apparatus as recited in claim 1, further comprising a first reflective grating formed in said optical transmission medium at a wavelength that provides maximum reflection of optical energy at a first input wavelength λ_{p1}, and a second reflective grating formed in said optical transmission medium at a wavelength that provides maximum reflection of optical energy at a second input wavelength λ_{p2}, wherein at least one of the first and second input wavelengths differs from the input wavelength λ_p.

4. The apparatus as recited in claim 1, wherein the gratings at wavelengths not corresponding to the gain maxima of the Raman-Stokes order shifts are within approximately ±20 nm of wavelengths that correspond to the gain maxima of the Raman-Stokes order shifts.

5. The apparatus as recited in claim 1, further comprising at least one reflective grating formed in said optical transmission medium at a wavelength that provides reflection with less than maximum efficiency, wherein the wavelength of the reflective grating does not correspond to the gain maxima of the Raman-Stokes order shift of the input wavelength λ_p but is within approximately ±20 nm of a wavelength that corresponds to the gain maxima of the Raman-Stokes order shift of the input wavelength λ_p.

6. The apparatus as recited in claim 1, wherein said optical transmission medium includes an input region and an output region, and wherein said at least one pair of gratings comprises at least one grating written in said input region and a complementary grating written in said output region.

7. A cascaded Raman resonator (CRR) (12) for converting optical energy to an output wavelength λ_n, said cascaded Raman resonator (CRR) comprising:

an optical transmission medium (32) for coupling to a source of optical energy having an input wavelength λ_p, said optical energy transmission medium including an input region (36) and an output region (34);
a first reflective grating (54) formed in the input region of said optical transmission medium, said first reflective grating corresponding to the output wavelength λ_n;
at least one second reflective grating (52) formed in the input region of said optical transmission medium, said second gratings corresponding to the intermediate Raman-Stokes order shifts λ_1, λ_2,...,λ_n, where n≥2;
at least one third reflective grating (44) formed in the output region of said optical transmission medium, said third gratings corresponding to the intermediate Raman-Stokes order shifts λ_1, λ_2..., λ_n, where n≥2, said third gratings complementing respective second gratings and forming grating pairs therewith in such a way that optical cavities are defined in said optical transmission medium for Raman scattering; and
at least one transmissive grating (46) written in the output region of said optical transmission medium at a wavelength that provides maximum reflectance of optical energy at the output wavelength λ_n, said transmissive grating complementing said first reflective grating and forming a grating pair therewith within said optical transmission medium,

characterized in that
the gratings of at least one grating pair formed by a second reflective grating and the respective third reflective grating are written at wavelengths that do not correspond to the gain maxima of the Raman-Stokes order shifts, wherein the optical energy is converted with less efficiency than if said reflective gratings were written at wavelengths that correspond to the gain maxima of the Raman-Stokes order shifts.

8. The apparatus as recited in claim 7, further comprising a reflective pump grating formed in the output region of said optical transmission medium at a wavelength that provides maximum reflection of optical energy at the input wavelength λ_p.

9. The apparatus as recited in claim 7, further comprising a reflective pump grating formed in the output region of said optical transmission medium at a wavelength that provides maximum reflection of optical energy at a first input wavelength λ_{p1}, and a second pump reflective grating formed in the output region of said optical transmission medium at a wavelength that provides maximum reflection of optical energy at a second input wavelength λ_{p2}, wherein at least one of the first and second input

wavelengths differs from the input wavelength λ_p.

10. The apparatus as recited in claim 7, wherein the gratings at wavelengths not corresponding to the gain maxima of the Raman-Stokes order shifts are written at wavelengths within approximately ±20 nm of wavelengths corresponding to the gain maxima of the Raman-Stokes order shifts.

11. The apparatus as recited in claim 7, further comprising at least one reflective grating formed in the output region of said optical transmission medium at a wavelength that provides reflection with less than maximum efficiency, wherein the wavelength of the reflective grating does not correspond to the gain maxima of the Raman-Stokes order shift of the input wavelength λ_p but is within approximately ±20 nm of the gain maxima of the Raman-Stokes order shift of the input wavelength λ_p.

12. An optical communications system (10), comprising:

a source of optical energy (14) having an input wavelength λ_p; and
a cascaded Raman resonator (12) optically coupled to said source, said cascaded Raman resonator having an input region (36) and an output region (34), wherein said input region includes a reflective grating (54) formed therein at a wavelength corresponding to an output wavelength λ_n, and at least one first reflective grating (52) formed therein at wavelengths corresponding to the intermediate Stokes orders $\lambda_1, \lambda_2, ..., \lambda_n$, where n≥2, and wherein said output region includes at least one second reflective grating (44) formed therein at wavelengths corresponding to the intermediate Stokes orders $\lambda_1, \lambda_2, ..., \lambda_n$, said second gratings complementing respective said first gratings and forming grating pairs therewith in such a way that optical cavities are defined in said cascaded Raman resonator, and a transmissive grating (46) formed therein at a wavelength corresponding to the output wavelength λ_n,
characterized in that
at least one pair of gratings formed by an input region grating and the corresponding output region grating is written at a wavelength that does not correspond to the gain maxima of the Raman-Stokes order shifts, wherein the optical energy is converted with less efficiency than if the gratings were written at wavelengths that correspond to the gain maxima of the Raman-Stokes order shifts wherein maximum reflection efficiency occurs at wavelengths that correspond to Raman-Stokes order shifts.

Patentansprüche

1. Vorrichtung zum Konvertieren von Lichtenergie innerhalb eines optischen Kommunikationssystems (10) mit einer Quelle von Lichtenergie (14) mit einer Eingangswellenlänge λ_p, wobei die Lichtenergie in eine Ausgangswellenlänge λ_n ramankonvertiert wird, die größer ist als die Eingangswellenlänge λ_p, wobei die Vorrichtung folgendes umfaßt:

ein an die Quelle von Lichtenergie angekoppeltes optisches Transmissionsmedium (32);
mindestens ein in dem optischen Transmissionsmedium ausgebildetes Gitterpaar (44, 46, 52, 54), das optische Hohlräume zur Strahlung von Lichtenergie mit der Ausgangswellenlänge λ_n definiert,

wobei die definierten optischen Hohlräume Lichtenergie mit der Eingangswellenlänge λ_p in Lichtenergie mit der Ausgangswellenlänge λ_n konvertieren,
dadurch gekennzeichnet, daß
mindestens ein Paar der Gitter in das optische Transmissionsmedium bei einer Wellenlänge geschrieben ist, die nicht der Maximalverstärkung für die Verschiebung bei Raman-Stokes-Ordnung entspricht, wobei die Lichtenergie mit weniger Effizienz konvertiert wird, als wenn die Gitter bei Wellenlängen geschrieben wären, die der Maximalverstärkung für die Verschiebungen bei Raman-Stokes-Ordnung entsprechen, wobei die maximale Reflexionseffizienz bei Wellenlängen auftritt, die Verschiebungen bei Raman-Stokes-Ordnung entsprechen.

2. Vorrichtung nach Anspruch 1, weiterhin mit einem in dem optischen Transmissionsmedium ausgebildeten reflektierenden Gitter mit einer Wellenlänge, die bei der Eingangswellenlänge λ_p eine maximale Reflexion von Lichtenergie liefert.

3. Vorrichtung nach Anspruch 1, weiterhin mit einem in dem optischen Transmissionsmedium ausgebildeten ersten reflektierenden Gitter mit einer Wellenlänge, die bei einer ersten Eingangswellenlänge λ_{p1} eine maximale Reflexion von Lichtenergie liefert, und einem in dem optischen Transmissionsmedium ausgebildeten zweiten reflektierenden Gitter mit einer Wellenlänge, die bei einer zweiten Eingangswellenlänge λ_{p2} eine maximale Reflexion von Lichtenergie liefert, wobei mindestens eine der ersten und zweiten Eingangswellenlänge sich von der Eingangswellenlänge λ_p unterscheidet.

4. Vorrichtung nach Anspruch 1, wobei die Gitter mit Wellenlängen, die nicht den Verstärkungsmaxima der Verschiebungen bei Raman-Stokes-Ordnung

entsprechen, innerhalb etwa ± 20 nm von Wellenlängen liegen, die den Verstärkungsmaxima der Verschiebungen bei Raman-Stokes-Ordnung entsprechen.

5. Vorrichtung nach Anspruch 1, weiterhin mit mindestens einem in dem optischen Transmissionsmedium ausgebildeten reflektierenden Gitter mit einer Wellenlänge, die eine Reflexion mit einer unter dem Maximum liegenden Effizienz liefert, wobei die Wellenlänge des reflektierenden Gitters nicht den Verstärkungsmaxima der Verschiebung bei Raman-Stokes-Ordnung mit der Eingangswellenlänge λ_p entspricht, sondern innerhalb etwa ± 20 nm einer Wellenlänge liegt, die den Verstärkungsmaxima der Verschiebung bei Raman-Stokes-Ordnung der Eingangswellenlänge λ_p entspricht.

6. Vorrichtung nach Anspruch 1, bei der das optische Transmissionsmedium einen Eingangsbereich und einen Ausgangsbereich aufweist und wobei das mindestens eine Paar Gitter mindestens ein in dem Eingangsbereich geschriebenes Gitter und ein in dem Ausgangsbereich geschriebenes komplementäres Gitter umfaßt.

7. Kaskadierter Ramanresonator (CRR) (12) zum Konvertieren von Lichtenergie in eine Ausgangswellenlänge λ_n, wobei der kaskadierte Ramanresonator (CRR) folgendes umfaßt:

   ein optisches Transmissionsmedium (32) zum Ankoppeln an eine Quelle von Lichtenergie mit einer Eingangswellenlänge λ_p, wobei das Lichtenergietransmissionsmedium einen Eingangsbereich (36) und einen Ausgangsbereich (34) aufweist;
   ein in dem Eingangsbereich des optischen Transmissionsmediums ausgebildetes erstes reflektierendes Gitter (54), wobei das erste reflektierende Gitter der Ausgangswellenlänge λ_n entspricht;
   mindestens ein in dem Eingangsbereich des optischen Transmissionsmediums ausgebildetes zweites reflektierendes Gitter (52), wobei die zweiten Gitter den dazwischenliegenden Verschiebungen bei Raman-Stokes-Ordnung $\lambda_1, \lambda_2, ..., \lambda_n$, entsprechen, wobei $n \geq 2$;
   mindestens ein in dem Ausgangsbereich des optischen Transmissionsmediums ausgebildetes drittes reflektierendes Gitter (44), wobei die dritten bei Gitter den dazwischenliegenden Verschiebungen Raman-Stokes-Ordnung $\lambda_1, \lambda_2, ... \lambda_n$, entsprechen, wobei $n \geq 2$, wobei die dritten Gitter die jeweiligen zweiten Gitter komplementieren und mit ihnen Gitterpaare bilden, so daß in dem optischen Transmissionsmedium optische Hohlräume für Raman-Streuung definiert werden; und
   mindestens ein in den Ausgangsbereich des optischen Transmissionsmediums geschriebenes transmissives Gitter (46) mit einer Wellenlänge, die maximales Reflexionsvermögen von Lichtenergie bei der Ausgangswellenlänge λ_n liefert, wobei das transmissive Gitter das erste reflektierende Gitter komplementiert und mit ihm im optischen Transmissionsmedium ein Gitterpaar bildet,

   dadurch gekennzeichnet, daß
   die Gitter von mindestens einem Gitterpaar, das durch ein zweites reflektierendes Gitter und das jeweilige dritte reflektierende Gitter gebildet wird, bei Wellenlängen geschrieben sind, die nicht den Verstärkungsmaxima für Verschiebungen bei Raman-Stokes-Ordnung entsprechen, wobei die Lichtenergie mit weniger Effizienz konvertiert wird, als wenn die reflektierenden Gitter bei Wellenlängen geschrieben wären, die den Verstärkungsmaxima für Verschiebungen bei Raman-Stokes-Ordnung entsprechen.

8. Vorrichtung nach Anspruch 7, weiterhin mit einem im Ausgangsbereich des optischen Transmissionsmediums ausgebildeten reflektierenden Pumpgitter mit einer Wellenlänge, die eine maximale Reflexion von Lichtenergie bei der Eingangswellenlänge λ_p liefert.

9. Vorrichtung nach Anspruch 7, weiterhin mit einem im Ausgangsbereich des optischen Transmissionsmediums ausgebildeten ersten reflektierenden Pumpgitter mit einer Wellenlänge, die eine maximale Reflexion von Lichtenergie bei einer ersten Eingangswellenlänge λ_{p1} liefert, und einem im Ausgangsbereich des optischen Transmissionsmediums ausgebildeten zweiten reflektierenden Pumpgitter mit einer Wellenlänge, die eine maximale Reflexion von Lichtenergie bei einer zweiten Eingangswellenlänge λ_{p2} liefert, wobei mindestens eine der ersten und zweiten Eingangswellenlänge sich von der Eingangswellenlänge λ_p unterscheidet.

10. Vorrichtung nach Anspruch 7, wobei die Gitter mit Wellenlängen, die nicht den Verstärkungsmaxima der Verschiebungen bei Raman-Stokes-Ordnung entsprechen, mit Wellenlängen geschrieben sind, die innerhalb etwa ± 20 nm von Wellenlängen liegen, die den Verstärkungsmaxima der Verschiebungen bei Raman-Stokes-Ordnung entsprechen.

11. Vorrichtung nach Anspruch 7, weiterhin mit mindestens einem in dem Ausgangsbereich des optischen Transmissionsmediums ausgebildeten reflektierenden Gitter mit einer Wellenlänge, die eine

Reflexion mit einer unter dem Maximum liegenden Effizienz liefert, wobei die Wellenlänge des reflektierenden Gitters nicht den Verstärkungsmaxima der Verschiebung bei Raman-Stokes-Ordnung mit der Eingangswellenlänge λ_p entspricht, sondern innerhalb etwa ± 20 nm der Verstärkungsmaxima der Verschiebung bei Raman-Stokes-Ordnung der Eingangswellenlänge λ_p entspricht.

12. Optisches Kommunikationssystem (10), das folgendes umfaßt:

eine Quelle von Lichtenergie (14) mit einer Eingangswellenlänge λ_p; und
einen optisch an die Quelle angekoppelten kaskadierten Ramanresonator (12), der einen Eingangsbereich (36) und einen Ausgangsbereich (34) aufweist, wobei der Eingangsbereich ein darin ausgebildetes reflektierendes Gitter (54) mit einer einer Ausgangswellenlänge λ_n entsprechenden Wellenlänge und mindestens ein darin ausgebildetes erstes reflektierendes Gitter (52) mit Wellenlängen aufweist, die den dazwischenliegenden Stokes-Ordnungen λ_1, λ_2, ..., λ_n entsprechen, wobei n ≥ 2, und wobei der Ausgangsbereich mindestens ein darin ausgebildetes zweites reflektierendes Gitter (44) mit Wellenlängen aufweist, die den dazwischenliegenden Stokes-Ordnungen λ_1, λ_2 ..., λ_n entsprechen, wobei die zweiten Gitter die jeweiligen ersten Gitter komplementieren und mit ihnen Gitterpaare bilden, so daß in dem kaskadierten Ramanresonator optische Hohlräume definiert werden, und darin ein transmissives Gitter (46) mit einer Wellenlänge ausgebildet ist, die der Ausgangswellenlänge λ_n entspricht,

dadurch gekennzeichnet, daß
mindestens ein Paar von durch ein Eingangsbereichsgitter und das entsprechende Ausgangsbereichsgitter gebildeten Gittern bei einer Wellenlänge geschrieben ist, die nicht den Verstärkungsmaxima für Verschiebungen bei Raman-Stokes-Ordnung entspricht, wobei die Lichtenergie mit weniger Effizienz konvertiert wird, als wenn die Gitter bei Wellenlängen geschrieben wären, die den Verstärkungsmaxima der Verschiebungen bei Raman-Stokes-Ordnung entsprechen, wobei die maximale Reflexionseffizienz bei Wellenlängen auftritt, die Verschiebungen bei Raman-Stokes-Ordnung entsprechen.

Revendications

1. Appareil pour convertir une énergie optique dans un système de communications optiques (10) comportant une source d'énergie optique (14) ayant une longueur d'onde d'entrée λ_p, dans lequel l'énergie optique est convertie par effet Raman en une longueur d'onde de sortie λ_n qui est supérieure à la longueur d'onde d'entrée λ_p, dans lequel ledit appareil comprend:

un milieu de transmission optique (32) couplé à la source d'énergie optique ;
au moins une paire de réseaux (44, 46, 52, 54) formés dans ledit milieu de transmission optique qui définit des cavités optiques en vue du rayonnement de l'énergie optique à ladite longueur d'onde de sortie λ_n ;

dans lequel les cavités optiques définies convertissent l'énergie optique de la longueur d'onde d'entrée λ_p en une énergie optique ayant la longueur d'onde de sortie λ_n,
caractérisé en ce que
au moins une paire des réseaux est écrite dans ledit milieu de transmission optique à une longueur d'onde qui ne correspond pas au gain maximum du décalage d'ordre selon Raman-Stokes, dans lequel l'énergie optique est convertie avec moins d'efficacité que si les réseaux étaient écrits à des longueurs d'onde qui correspondent au gain maximum des décalages d'ordres selon Raman-Stokes dans lesquels une efficacité de réflexion maximum se produit à des longueurs d'onde qui correspondent aux décalages d'ordres selon Raman-Stokes.

2. Appareil selon la revendication 1, comprenant en outre un réseau réflecteur formé dans ledit milieu de transmission optique à une longueur d'onde qui fournit une réflexion maximum d'énergie optique à la longueur d'onde d'entrée λ_p.

3. Appareil selon la revendication 1, comprenant en outre un premier réseau réflecteur formé dans ledit milieu de transmission optique à une longueur d'onde qui fournit une réflexion maximum d'énergie optique à une première longueur d'onde d'entrée λ_{p1}, et un deuxième réseau réflecteur formé dans ledit milieu de transmission optique à une longueur d'onde qui fournit une réflexion maximum d'énergie optique à une deuxième longueur d'onde d'entrée λ_{p2}, dans lequel au moins une des première et deuxième longueurs d'onde d'entrée diffère de la longueur d'onde d'entrée λ_p.

4. Appareil selon la revendication 1, dans lequel les réseaux à des longueurs d'onde ne correspondant pas aux maxima de gain des décalages d'ordre selon Raman-Stokes sont situés approximativement à ± 20 nm de longueurs d'onde qui correspondent aux maxima de gain des décalages d'ordres selon Raman-Stokes.

5. Appareil selon la revendication 1, comprenant en outre au moins un réseau réflecteur formé dans ledit milieu de transmission optique à une longueur d'onde qui fournit une réflexion avec une efficacité inférieure à l'efficacité maximum, dans lequel la longueur d'onde du réseau réflecteur ne correspond pas aux maxima de gain des décalages d'ordres selon Raman-Stokes de la longueur d'onde d'entrée λ_p mais est située approximativement à ± 20 nm d'une longueur d'onde qui correspond aux maxima de gain du décalage d'ordre selon Raman-Stokes de la longueur d'onde d'entrée λ_p.

6. Appareil selon la revendication 1, dans lequel ledit milieu de transmission optique comporte une région d'entrée et une région de sortie, et dans lequel au moins une paire de réseaux comprend au moins un réseau écrit dans ladite région d'entrée et un réseau complémentaire écrit dans ladite région de sortie.

7. Résonateur de Raman en cascade (CRR) (12) pour convertir une énergie optique en une longueur d'onde de sortie λ_n, ledit résonateur de Raman en cascade (CRR) comprenant :

un milieu de transmission optique (32) pour le couplage à une source d'énergie optique ayant une longueur d'onde d'entrée λ_p, ledit milieu de transmission d'énergie optique comportant une région d'entrée (36) et une région de sortie (34);
un premier réseau réflecteur (54) formé dans la région d'entrée dudit milieu de transmission optique, ledit premier réseau réflecteur correspondant à la longueur d'onde de sortie λ_n ;
au moins un deuxième réseau réflecteur (52) formé dans la région d'entrée dudit milieu de transmission optique, lesdits deuxièmes réseaux correspondant aux décalages d'ordres selon Raman-Stokes intermédiaires λ_1, λ_2,... λ_n où $n \geq 2$;
au moins un troisième réseau réflecteur (44) formé dans la région de sortie dudit milieu de transmission optique, lesdits troisièmes réseaux correspondant aux décalages d'ordres selon Raman-Stokes intermédiaires λ_1 , λ_2,..., λ_n où $n \geq 2$, lesdits troisièmes réseaux complémentant des deuxièmes réseaux respectifs et formant des paires de réseaux avec ceux-ci de manière à définir des cavités optiques dans ledit milieu de transmission optique pour la diffusion de Raman ; et
au moins un réseau de transmission (46) écrit dans la région de sortie dudit milieu de transmission optique à une longueur d'onde qui fournit une réflectance maximum de l'énergie optique à la longueur d'onde de sortie λ_n, ledit réseau de transmission complémentant ledit premier réseau réflecteur et formant une paire de réseaux avec celui-ci à l'intérieur dudit milieu de transmission optique,

caractérisé en ce que
les réseaux d'au moins une paire de réseaux formée par un deuxième réseau réflecteur et le troisième réseau réflecteur respectif sont écrits à des longueurs d'onde qui ne correspondent pas aux maxima de gain des décalages d'ordres selon Raman-Stokes, dans lequel l'énergie optique est convertie avec moins d'efficacité que si lesdits réseaux réflectifs étaient écrits à des longueurs d'onde qui correspondent aux maxima de gain des décalages d'ordres selon Raman-Stokes.

8. Appareil selon la revendication 7, comprenant en outre un réseau de pompage réflecteur formé dans la région de sortie dudit milieu de transmission optique à une longueur d'onde qui fournit une réflexion maximum d'énergie optique à la longueur d'onde d'entrée λ_p.

9. Appareil selon la revendication 7, comprenant en outre un réseau de pompage réflecteur formé dans la région de sortie dudit milieu de transmission optique à une longueur d'onde qui fournit une réflexion maximum d'énergie optique à une première longueur d'onde d'entrée λ_{p1}, et un deuxième réseau de pompage réflecteur formé dans la région de sortie dudit milieu de transmission optique à une longueur d'onde qui fournit une réflexion maximum d'énergie optique à une deuxième longueur d'onde d'entrée λ_{p2}, dans lequel au moins une des première et deuxième longueurs d'onde diffère de la longueur d'onde d'entrée λ_p.

10. Appareil selon la revendication 7, dans lequel les réseaux à des longueurs d'onde ne correspondant pas aux maxima de gain des décalages d'ordres selon Raman-Stokes sont écrits à des longueurs d'onde comprises approximativement à ± 20 nm de longueurs d'onde qui correspondent aux maxima de gain des décalages d'ordres selon Raman-Stokes.

11. Appareil selon la revendication 7, comprenant en outre au moins un réseau réflecteur formé dans la région de sortie dudit milieu de transmission optique à une longueur d'onde qui fournit une réflexion avec une efficacité inférieure à l'efficacité maximum, dans lequel la longueur d'onde du réseau réflecteur ne correspond pas aux maxima de gain du décalage d'ordre selon Raman-Stokes de la longueur d'onde d'entrée λ_p mais est située approximativement à ± 20 nm des maxima de gain du décalage d'ordre selon Raman-Stokes de la longueur d'onde d'entrée λ_p.

12. Système de communications optiques (10),

comprenant :

une source d'énergie optique (14) ayant une longueur d'onde d'entrée λ_p ; et

un résonateur de Raman en cascade (14) couplé optiquement à ladite source, ledit résonateur de Raman en cascade ayant une région d'entrée (36) et une région de sortie (34), dans lequel ladite région d'entrée comporte un réseau réflecteur (54) formé dans celle-ci à une longueur d'onde correspondant à une longueur d'onde de sortie λ_n, et au moins un premier réseau réflecteur (52) formé dans celle-ci à des longueurs d'onde correspondant aux ordres de Stokes intermédiaires $\lambda_1, \lambda_2, ..., \lambda_n$ où $n \geq 2$, et dans lequel ladite région de sortie comporte au moins un deuxième réseau réflecteur (44) formé dans celle-ci à des longueurs d'onde correspondant aux ordres de Stokes intermédiaires λ_1 , $\lambda_2, ..., \lambda_n$, lesdits deuxièmes réseaux complémentant lesdits premiers réseaux respectifs et formant des paires de réseaux avec ceux-ci de manière à définir des cavités optiques dans ledit résonateur de Raman en cascade, et un réseau de transmission (46) formé dans celle-ci à une longueur d'onde correspondant à la longueur d'onde de sortie λ_n,

caractérisé en ce que

au moins une paire de réseaux formée par un réseau dans la région d'entrée et le réseau correspondant dans la région de sortie est écrite à une longueur d'onde qui ne correspond pas aux maxima de gain des décalages d'ordres selon Raman-Stokes, dans lequel l'énergie optique est convertie avec moins d'efficacité que si les réseaux étaient écrits à des longueurs d'onde qui correspondent aux maxima de gain des décalages d'ordres selon Raman-Stokes, dans lequel l'efficacité de réflexion maximum se produit à des longueurs d'onde qui correspondent aux décalages d'ordres selon Raman-Stokes.

FIG. 1

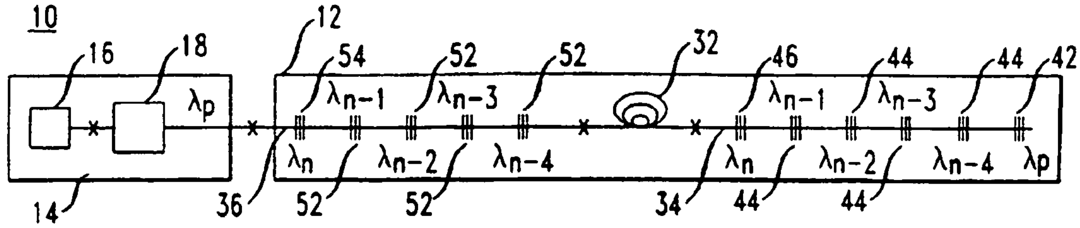


FIG. 2A

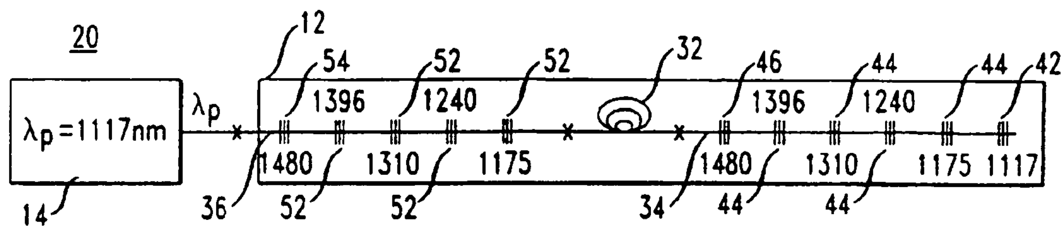


FIG. 2B

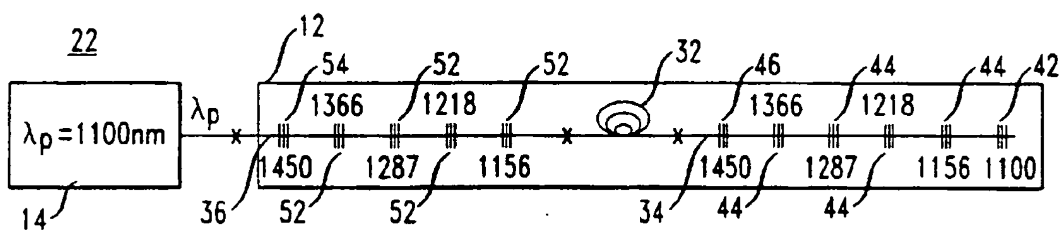


FIG. 3

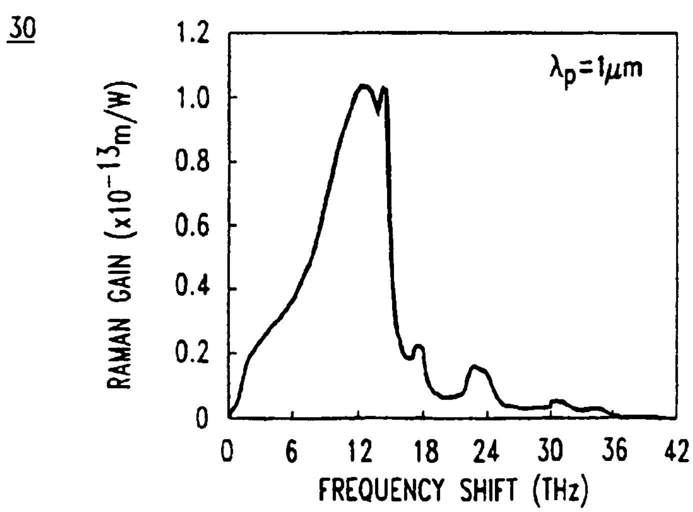


FIG. 4

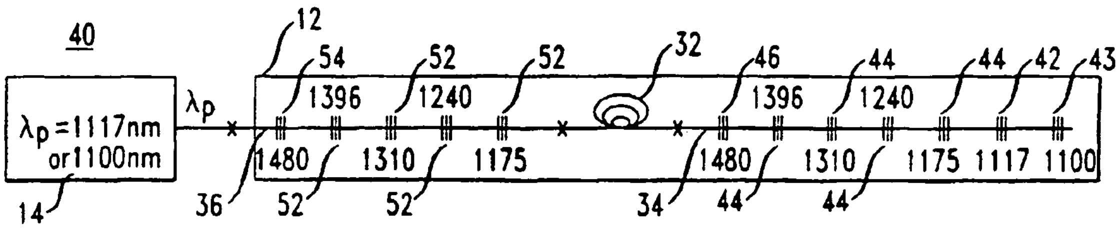


FIG. 5

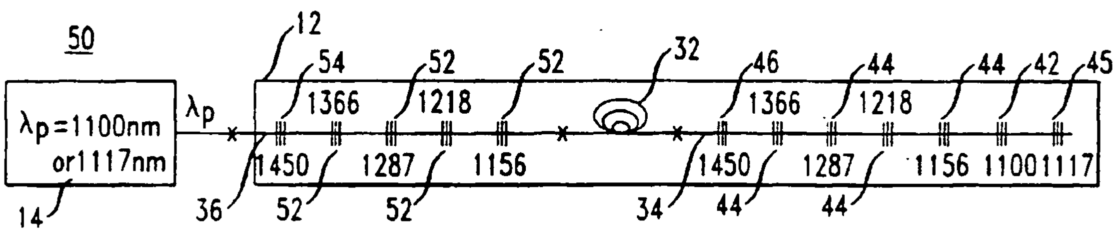


FIG. 7

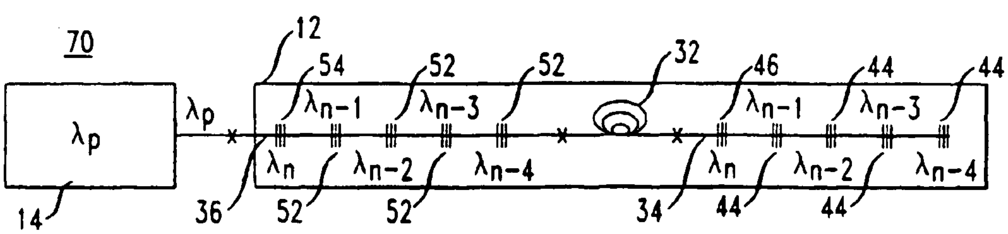


FIG. 6A

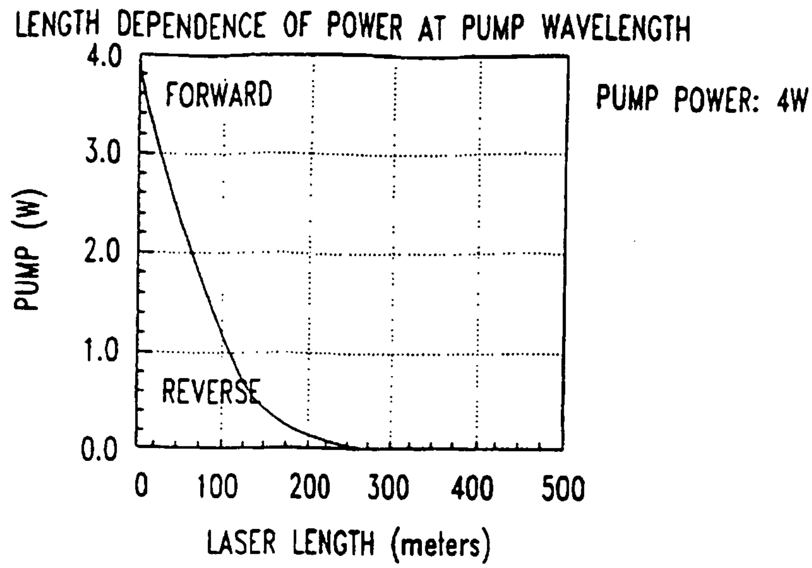
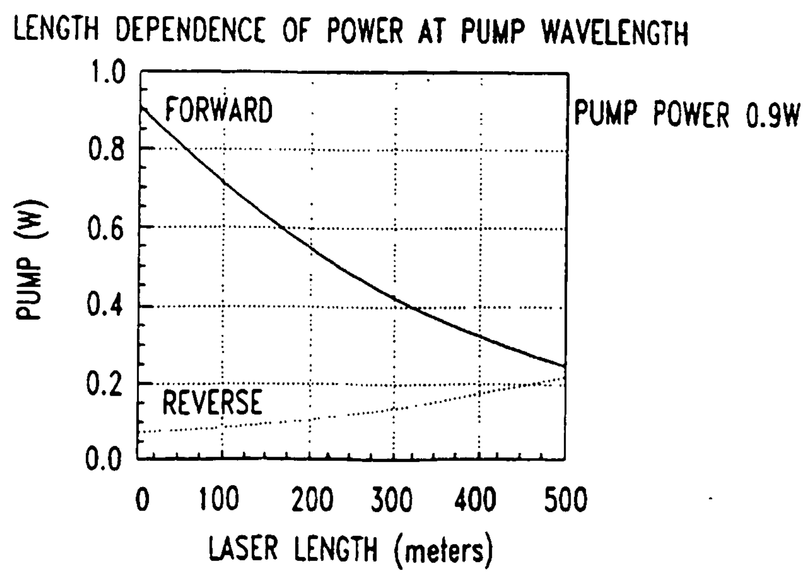

LENGTH DEPENDENCE OF POWER AT PUMP WAVELENGTH
4.0
3.0
2.0
1.0
0.0
PUMP (W)
FORWARD
REVERSE
PUMP POWER: 4W
0
100
200
300
400
500
LASER LENGTH (meters)

FIG. 6B


LENGTH DEPENDENCE OF POWER AT PUMP WAVELENGTH
1.0
0.8
0.6
0.4
0.2
0.0
PUMP (W)
FORWARD
REVERSE
PUMP POWER 0.9W
0
100
200
300
400
500
LASER LENGTH (meters)